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Radiological Dose Assessment

Robert J. Harrach
Gretchen M. Gallegos
S. Ring Peterson

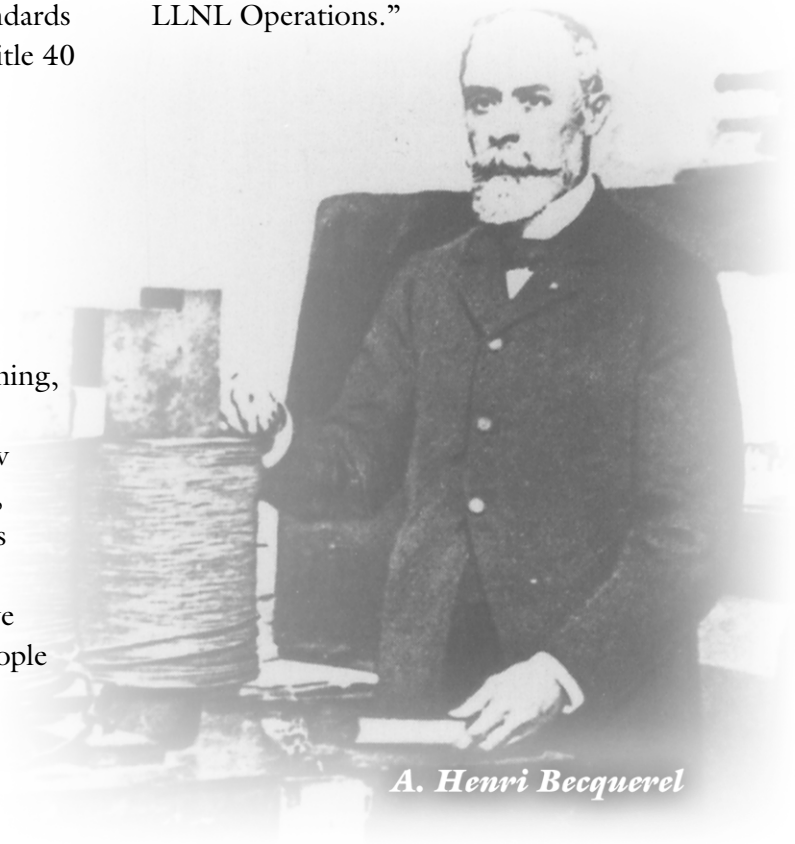
Introduction

Radiological doses to the public result from both natural and man-made radiation. The doses received by individuals and populations can be determined by measurements and calculations. This chapter describes Lawrence Livermore National Laboratory's radiological dose assessments, which are made to determine the impact of LLNL operations on the public and the environment. It includes a discussion of the analyses performed to demonstrate LLNL's compliance with the radiological National Emission Standards for Hazardous Air Pollutants (NESHAPs; Title 40 *Code of Federal Regulations* [CFR], Part 61, Subpart H).

Background Information

Because this chapter is written for a diverse readership, from scientists and regulators to interested citizens with limited scientific training, a description is given of concepts, methods, tools, and other basic material in the first few sections as well as in Appendix D. Part D-1, Radiation Basics, covers the different sources and types of radiation and the units used to quantify radiation, and it provides perspective on the wide range of radiation levels that people commonly encounter. Part D-2, Radiation Control Measures at LLNL, sketches the standard operating procedures used to protect employees, the public, and the environment from uncontrolled releases and unsafe levels of radiation.

A discussion of sources, principal public receptors, and other aspects of modeling and monitoring follows the introductory material in the main text, leading to a presentation of key results on dose impacts from operations conducted in 2000. Readers desiring to go directly to these principal new results can turn to the section "Radiological Doses to the Public from 2000 LLNL Operations."



A. Henri Becquerel

Releases of Radioactivity to Air

Releases to the air are by far the major source of public radiological exposures from LLNL operations. In contrast, releases to groundwater, surface water, and sewerable water are not sources of direct public exposures because these waters are not directly consumed or used by the public. Water releases can cause indirect exposures, which are treated as special cases; for example, a recent case considered the possible dose to the public from inhalation and ingestion of soil contaminated by sewer effluent containing radioactivity (U.S. Department of Health and Human Services 1999). Apart from such unusual occurrences, measurements and modeling of releases to air determine LLNL's radiological dose to the public.

Data are gathered by three principal means: routine surveillance air monitoring for radioactive particles and gases, both on and off Laboratory property (described in Chapter 5); continuous monitoring of stack effluent at selected facilities at the Livermore site (described in Chapter 4); and usage inventories at all noncontinuously monitored or unmonitored facilities housing radioactive materials management areas and for radioactive materials used in explosive experiments at Site 300 (described in LLNL's NESHAPs annual reports [e.g., Gallegos et al. 2001]).

Despite this emphasis on air monitoring, it should be noted that LLNL's extensive environmental monitoring program encompasses a variety of media and a wide range of potential contaminants; it is not limited to radioactive ones. In addition to air monitoring and the three categories of water monitoring already mentioned, the Laboratory samples soil, sediment, vegetation, and wine, and measures environmental (gamma) radiation. Monitoring has been described extensively since 1971 in LLNL's environmental reports (e.g., Larson et al. 2000; see also Chapters 4 through 12 in the present report) and in LLNL's triennially updated *Environmental Monitoring Plan* (e.g., Tate et al. 1999) and its associated procedures and guidance documents.

Air Dispersion and Dose Models

Theoretical/calculational models are needed to describe the transport and dispersion in air of contaminants and the doses received by exposed persons. Various factors dictate this need for modeling: (1) the amounts of LLNL-generated radioactive material dispersed into the atmosphere cause doses thousands of times smaller than those caused by natural background radiation (arising from irradiation by cosmic rays, inhalation of radon gas, exposure to radioactive materials in soil and rock, and ingestion of naturally occurring radionuclides present in our food and water; see Appendix D, Part D-1), so it is difficult to demonstrate compliance with standards through physical measurements alone; (2) all potentially significant exposure pathways need to be taken into account when estimating dose impacts; and (3) the U.S. Department of Energy (DOE) and the U.S. Environmental Protection Agency (EPA) sanction the use of specific computer codes that implement their approved dosimetry and dispersion models for evaluating potential doses to the public from both routine and unplanned releases. Advantages of a well-developed modeling capability include its utility in source design and optimization (e.g., estimating effects of hypothetical and/or dangerous sources) and in interpreting past events (e.g., in dose reconstruction).

The computer programs used at LLNL to model air releases and their impacts feature idealized, Gaussian-shaped plumes and can be run on personal computers. The CAP88-PC code (Parks 1992), in particular, incorporates dosimetric and health effects data and equations that are mandated by EPA to be used in compliance assessments.

Furthermore, CAP88-PC accommodates site-specific input data files to characterize meteorological conditions and population distributions for both individual and collective dose evaluations, and the code is relatively easy to use and understand. For these reasons, CAP88-PC has been the "workhorse" modeling tool for LLNL's regulatory compliance assessments since its availability in March 1992, particularly as applied to chronic releases of radioactivity to air occurring in the course of routine operations.

Radiation Protection Standards

The release of radionuclides from operations at LLNL and the resultant radiological impact to the public are regulated by both DOE and EPA.

DOE environmental radiation protection standards, provided under the authority of the Atomic Energy Act of 1954 and the DOE Organization Act of 1977 (both as amended), are defined in DOE Order 5400.5, *Radiation Protection of the Public and the Environment*. The standards for controlling exposures to the public from operations at DOE facilities that are incorporated in this order are based on recommendations by the International Commission on Radiological Protection (ICRP). The radiological impact to the public is assessed in accordance with the applicable portions of DOE Order 5400.1, *General Environmental Protection*. Current indices and links to DOE orders appear on the Department of Energy Directives website: http://www.directives.doe.gov.

The primary DOE radiation standards for protection of the public are 1 millisievert per year (1 mSv/y) or 100 millirem per year (100 mrem/y) whole-body effective dose equivalent (EDE) for prolonged exposure of a maximally exposed individual in an uncontrolled area and 5 mSv/y (500 mrem/y) EDE for occasional exposure of this individual. (EDEs and other technical terms are discussed in Appendix D, Part D-1 and defined in the glossary of this report.) These limits pertain to the sum of the EDE from external radiation and the committed 50-year EDE from radioactive materials ingested or inhaled during a particular year that may remain in the body for many years.

Radionuclide emissions to the atmosphere from DOE facilities are further regulated by the EPA, under the authority of Section 112 of the Clean Air Act. Subpart H of NESHAPs, under 40 CFR 61, sets standards for public exposure to airborne radioactive materials (other than radon) released by DOE facilities; radon is regulated by Subparts Q and T. NESHAPs implements the dosimetry system recommended by the ICRP in Publication 26 (ICRP 1977).

The EPA's radiation dose standard, which applies only to air emissions, limits the EDE to members of the public caused by activities/operations at a DOE facility to 100 µSv/y (10 mrem/y). EPA regulations specify not only the allowed levels, but also the approved methods by which airborne emissions and their impacts must be evaluated. With respect to all new and/or modified projects, NESHAPs compliance obligations define the requirements to install continuous air effluent monitoring and to obtain EPA approval for startup of operations. NESHAPs regulations require that any operation with the potential to produce an annual-averaged off-site dose greater than or equal to 1 µSv/y (0.1 mrem/y), taking full credit for emission-abatement devices, such as high-efficiency particulate air (HEPA) filters, must obtain EPA approval prior to startup of operations. This same calculation, but without taking any credit for emission abatement devices, determines whether or not continuous monitoring of emissions to air from this project is required. These requirements are spelled out in LLNL's online *Environment, Safety, and Health (ES&H) Manual* in Document 31.1, "Air Quality Compliance," which can be found at the

following Internet address: http://www.llnl.gov/es_and_h/hsm/doc_31.01/doc31-01.html.

Reporting Requirements

All DOE facilities that conduct significant environmental protection programs are required by DOE to prepare an annual environmental report for the site, covering activities of the previous calendar year involving releases to all media via all pathways. Because DOE facilities and operations are subject to the regulatory requirements of EPA, in particular 40 CFR 61, Subpart H, DOE facilities are further required to submit an annual report to the EPA, via DOE, showing compliance with NESHAPs (addressing only releases to air).

Details on reporting requirements and citation of pertinent DOE orders and federal regulations are available in the chapter on radiological dose assessment in earlier environmental reports (e.g., Harrach et al. 1997) or LLNL's radiological dose assessment guidance document (Harrach 1998).

Evaluation of Sources of Radioactive Emissions

The starting point for an assessment of radiological dose is to identify and properly characterize all significant sources of radioactive emissions at a site. LLNL's sources are determined in three principal ways: (1) by an inventory process, (2) by direct measurement of the emission rate at the source (continuous effluent monitoring), and (3) by monitoring airborne gases and particulate matter at selected field points in and around the Livermore site and Site 300 (continuous surveillance air monitoring).

Inventoried Sources

Radiological operations areas are any locations where radioactive materials are used or stored, or where activation products occur. Several such areas at the Livermore site have effluent monitoring systems in place in their exhaust pathways, allowing a direct measurement of their emission rates. For unmonitored or noncontinuously monitored radiological operations areas, source terms for potential releases are inferred from radionuclide inventories, in accordance with EPA methods.

Experimenters and facility managers provide inventory data, following a protocol designed and administered by LLNL's Environmental Protection Department. A full (100%) inventory is conducted every three years, including 1994, 1997, and 2000. Only the key Livermore site facilities, defined as those in a ranked list that collectively accounted for 90% or more of the previous year's Livermore site radiological dose to members of the public, are reinventoried annually. In addition, all new radiological operations areas (ones that commenced operations in the year under evaluation) are inventoried, and data on radionuclides used in all Site 300 explosives experiments are provided each year. A description of LLNL's inventory process, including examples of the inventory form and accompanying instructions, is given in the guidance document for preparation of NESHAPs annual reports (Gallegos 1998).

For dose-assessment modeling of unmonitored or noncontinuously monitored sources, the effective emission rate is calculated from radiological usage inventories by applying EPA-specified fractions for potential release to air of materials in different physical states (solid, liquid, powder, or gas) for each radioisotope. The inventory quantity (in becquerels or curies) is multiplied by a state-dependent release fraction to give the potential annual release to air, i.e., the effective emission rate, in

accordance with 40 CFR 61, Appendix D. If the material is an unconfined gas, the release fraction is 1.0; for liquids and powders, 1.0×10^{-3} is used; and for solids, 1.0×10^{-6}. In the same way, if the radioactive material is encapsulated or sealed for the entire year (i.e., it was not used and release to air was prevented), then its release fraction is considered to be zero. For materials that were encapsulated or sealed for part of the year, or that resided in different facilities over the course of the year, time weighting factors are introduced to properly account for the release potential. Information on inventories and descriptions of the diffuse sources can be found in the guidance document (Gallegos 1998) and in NESHAPs annual reports.

Monitored Sources

Stack Effluent Monitoring

Actual measurements of radionuclides in effluent flow are the basis for reported emissions from continuously monitored sources. Six buildings at the Livermore site had continuously monitored discharge points in 2000: Buildings 175, 177, 251, 331, 332, and 491; taken together, these buildings feature 76 continuously operating monitors. The monitoring systems are described in the *LLNL NESHAPs 2000 Annual Report* (Gallegos et al. 2001), as well as in Chapter 4.

The most significant monitored source in terms of public dose impact is the Tritium Facility, Building 331, at the Livermore site. Each of the two 30-m stacks on this facility has both a continuous-monitoring ion-chamber alarm system and continuous molecular-sieve samplers (see Chapter 4 in the Data Supplement). The sieve samplers, which can discriminate between tritiated water vapor (HTO) and molecular tritium gas (HT), provide the values used for environmental reporting. The alarmed ion chambers provide real-time tritium concentration for significant releases (HT plus HTO). Monitoring of these stacks provides an accurate measure of the total quantity (in becquerels or curies) of tritium released to the environment, time-resolved over the course of the year. Because the stacks have known properties (height, flow rate, and diameter) and the wind field properties (wind speed, direction, and fluctuation characteristics) are continuously monitored, these data are optimal inputs to modeling, and the quality of these data affects the accuracy of air dispersion and dose assessment modeling more than any other input factors.

Discharge points at Buildings 175, 177, 251, 332, and 491 are monitored for gross alpha and gross beta radioactivity. Air samples for particulate emissions are extracted downstream of HEPA filters and prior to the discharge point to the atmosphere. Particles are collected on membrane filters. Sample results are generally found to be below the minimum detectable concentration (MDC) of the analysis; for details, see Chapter 4 in this report and the *LLNL NESHAPs 2000 Annual Report* (Gallegos et al. 2001).

Among the six continuously monitored facilities at the Livermore site, only the Plutonium Facility (Building 332) requires monitoring under the EPA's 0.1-mrem/y standard alluded to in the subsection Radiation Protection Standards. The other five are continuously monitored for programmatic or other reasons. For example, continuous monitoring is maintained at the Tritium Facility (Building 331) to provide the most dependable and accurate information on stack releases of tritium, the most significant radionuclide at the Livermore site in terms of potential public dose impact. Continuous monitoring is maintained at the Heavy Elements Facility (Building 251) in lieu of undertaking a modeling and measurement effort that would be required to demonstrate that monitoring is not needed.

Dose calculations based on effluent monitoring data are expected to be considerably more accurate than those relying on usage-inventory data, physical-state release-to-air fractions, emission-abatement factors, and time factors.

Surveillance Air Monitoring

To provide wide-area coverage complementing the stack effluent monitoring, surveillance air monitors are placed at selected locations at the Livermore site and Site 300 and in their vicinities to detect radioactive gases and particulate matter in ambient air. In addition, dose rates from external penetrating radiation (gamma rays) are measured using thermoluminescent dosimeters (TLDs). Siting of the air monitors and TLDs is done in accordance with the LLNL *Environmental Monitoring Plan* (Tate et al. 1999). Surveillance air monitors are also placed in the vicinity of known diffuse (extended area) emission sources at the Livermore site, specifically those associated with Buildings 292, 331, 514, and 612. Such monitors are also located in and around the Livermore site's southeast quadrant, and at on-site locations that provide wide coverage of Site 300. These special monitors measure the concentrations of radionuclides present in the air near the sources and allow a direct determination of their environmental impact (see Chapter 5). The surveillance air monitors not only are useful in gauging releases from routine operations; they have also proven valuable in quantifying the magnitude of accidental releases and their dose impacts.

Determinations of Dose

This section briefly describes the way LLNL estimates doses to the public for compliance purposes. It touches on the main modeling approaches, identifies the key hypothetical receptors that represent the most exposed public individuals, discusses some important aspects regarding the modeling of tritium, and briefly notes some of the special modeling challenges raised by diffuse sources and explosives experiments.

Principal Modeling Approaches

LLNL's primary calculational tool for estimating dose and risk to the public from routine operations and most unplanned releases is the computer code CAP88-PC. The user's guide (Parks 1992) provides useful information on the code, including discussions of the basic equations and key input and output files. Additional information, for example, about LLNL-site-specific data files and several important caveats on use of the code, has been presented in earlier environmental reports (e.g., Harrach et al. 1998) and more fully in the LLNL radiological dose assessment guidance document (Harrach 1998).

Other codes such as EPA's INPUFF code (Peterson and Lavdas 1986) or LLNL's HOTSPOT code (Homann 1994) can be used as needed to address unplanned releases or transient releases from normal operations or accidents. In 2000 the EPA granted regulatory "guideline model" status to two codes—the AERMOD and CALPUFF codes—which are of considerably greater complexity than CAP88-PC, INPUFF, and HOTSPOT. Many other Gaussian-plume-type computer models are available for modeling various types of releases; see, for example, the annotated lists in *Atmospheric Dispersion Modeling Resources* (Oak Ridge 1995) and *Supplement B to the Guideline on Air Quality Models (Revised)* (U.S. EPA 1993).

A complementary approach to deriving EDEs using the built-in dosimetry model in CAP88-PC or other codes is to explicitly calculate them using mathematical formulas from, for example, the Nuclear Regulatory Commission's Regulatory

Guide 1.109 (U.S. NRC 1977), which incorporate dose conversion factors consistent with those in the International Commission on Radiation Protection's Publication 30 (ICRP 1980). This approach, outlined in Appendix A of this report, has been used historically at LLNL (since 1979) and can be used to evaluate annual doses to the public inferred from sampling of local environmental media (air, water, vegetation, and wine).

Identification of Key Receptors

When assessing probable off-site impacts, LLNL pays particular attention to three potential doses. First is the dose to the sitewide maximally exposed individual member of the public (SW-MEI; defined below). Second is the dose to the maximally exposed individual (MEI) member of the public from a given emission point. Third is the collective or population dose received by people residing within 80 km of either of the two LLNL sites, adding the products of individual doses received and the number of people receiving them.

The SW-MEI is defined as the hypothetical member of the public at a single, publicly accessible location (where members of the public reside or abide) who receives the greatest LLNL-induced EDE from all sources at a site (e.g., the Livermore site). This dose sums the contributions of all emission points for evaluation under the EPA's 100 μSv/y (10 mrem/y) standard. Public facilities that could be the location of the SW-MEI include schools, churches, businesses, and residences. This hypothetical person is assumed to reside at this location 24 hours per day, 365 days per year, continuously breathing air having the ground-level radionuclide concentration, and consuming a specified fraction of food and drinking water that is affected by the releases of radioactivity from the site. Thus, the SW-MEI dose is not received by any actual individual and is used as a health-conservative estimate (i.e., overestimate) of the highest possible dose to any member of the public. The location of the SW-MEI is sensitive to the frequency distribution of wind speeds and directions and locations of key sources in a given year and can change from one year to the next. At the Livermore site, evaluation showed that the SW-MEI in 2000 was, as in previous years, located at the UNCLE Credit Union, about 10 m outside the controlled eastern perimeter of the site. This location lies 948 m from the Tritium Facility (Building 331), in an east-northeast direction (the typical prevailing wind direction). At Site 300, the 2000 SW-MEI occupied a new position, on the south-central boundary of the site bordering the Carnegie State Vehicular Recreation Area, approximately 3.2 km south-southeast of the firing table at Building 851. For the past several years the Site 300 SW-MEI location was an experimental area termed "Bunker 2," operated by Primex Physics International, just outside the east-central boundary of Site 300; Primex terminated operations at this facility.

The location of the MEI is generally different for each emission point. The MEI dose is used to evaluate whether continuous monitoring of each particular emission point is required and whether it is necessity to petition the EPA for permission to start up an activity (new or modified project), as discussed in the Reporting Requirements section.

Doses to the MEI, with and without allowance for abatement, are a major consideration when new projects or changes to existing projects (in which releases of radioactivity to the environment may occur) are reviewed for joint compliance with NESHAPs and the National Environmental Policy Act (NEPA). The possible environmental and worker safety issues raised by each proposed activity or project are examined from several different points of view in a process coordinated by LLNL's Environmental Protection Department, including a review and evaluation of potential emissions of

radionuclides and air toxics. Air-quality compliance requirements for projects are described in Document 31.1, "Air Quality Compliance," of LLNL's online *ES&H Manual* at the Internet address: http://www.llnl.gov/es_and_h/hsm/doc_31.01/doc31-01.html.

Assessment Assumptions Regarding Tritium

Several aspects of tritium dose estimates based on CAP88-PC should be noted.

Relative Contributions to Dose from HTO and HT Emissions

Tritium (^{3}H) emissions account for the major dose from operations at the Livermore site. These emissions exist in two major chemical forms: tritium oxide or tritiated water vapor (HTO) and tritium gas (HT). The doses received by exposure to these two forms differ greatly. HTO enters the body by ingestion, inhalation, and dermal absorption; HT enters by inhalation. Ingested HTO is distributed throughout the entire body and eliminated at the same rate as body water (apart from the small fraction metabolized). Inhaled HTO dissolves in the fluids of the lung and is absorbed. In contrast, very little of the HT that enters the body via inhalation is retained; most is exhaled. The EDE from inhalation of tritium gas is lower by a factor of about 10,000 than that from tritium oxide inhalation (ICRP 1994 and 1996), and, overall, HTO is traditionally considered to be 25,000 times more toxic than HT (Eckerman et al. 1988; ICRP 1979). HT requires conversion to HTO (oxidation) to produce significant dose.

Emissions of HTO are expected to be the major contributor to the tritium dose, particularly for nearby individual receptors, such as the MEI and SW-MEI; historically, LLNL's standard procedure has been to enter into CAP88-PC only the curies of HTO released to air, disregarding the HT component. A more conservative approach would be to treat all HT as HTO in tritium dose calculations. In April 1999, EPA mandated that LLNL do exactly that when calculating dose to the public for NESHAPs compliance purposes. It should be noted that this HT "dual" doses problem concerns only the Livermore site; at Site 300, tritium makes a negligible contribution to the public dose.

Whether the Livermore site SW-MEI dose and population dose are much affected by the different ways of including HT emissions depends on the balance of curies released as HT vs. HTO, and the degree to which tritium dominates other radionuclides in the calculation of potential dose. For example, in 1999, Tritium Facility emissions were divided between 214 curies of HTO and 67 curies of HT, HTO accounted for about 92% of the total dose, and the result of treating HT as HTO for the 1999 assessment was to increase the Livermore site dose to the SW-MEI by about 21%, compared to the value obtained by neglecting the contribution of HT to the SW-MEI dose. The 1999 population dose from Livermore site operations, which gives greater weight to the emissions from the tall stacks of the Tritium Facility than does the SW-MEI dose, was increased by 28% when treating HT as though it were HTO. However, in 2000 these stacks released 35.4 curies as HTO and only 4.8 curies as HT, and HTO accounted for about 75% of the total dose. As reported below in the section on Radiological Doses to the Public from 2000 LLNL Operations, the SW-MEI dose for 2000 was increased less than 3% by treating HT as though it were HTO, and the population dose increased by less than 11%. This chapter emphasizes doses excluding contributions from HT, both to provide continuity with doses reported in this annual environmental report in the past, and because we believe it is more accurate to do so than to represent HT as fully converted to HTO.

Dose-Rate-Conversion Factor for Tritium

The dose-rate-conversion factor that CAP88-PC uses for inhalation-plus-dermal-absorption of tritium is outdated and more conservative than the values quoted in recent literature. The ICRP in its Publication 30 (ICRP 1979) recommended that skin intake should be 50% of lung intake, revising its earlier recommendation stated in Publication 2 (ICRP 1959) that skin intake equals lung intake. The CAP88-PC dose-rate-conversion factor for tritium contains the 1959 recommendation, producing an inhalation-plus-dermal-absorption dose that is too large by a factor 4/3 relative to the more recent recommendation; see Attachment 3 in the *NESHAPs 1995 Annual Report* (Gallegos et al. 1996).

Overestimate of Ingestion Dose for Tritium

CAP88-PC overestimates the ingestion dose from tritium in a manner that depends on input selections, according to a recent article by Barry Parks (Parks 1999). The cause can be traced to three key assumptions implicit in the software that may not be immediately apparent to the user: (1) the contribution of homegrown food, (2) the distances at which food is produced, and (3) the number of people consuming locally produced food. Documentation on how these overestimates can occur is also available on the Internet at the following address: http://www.er.doe.gov/production/er-80/cap88/tritium.html.

Contribution from Ingestion of Organically Bound Tritium

The dose-rate-conversion factor for ingestion of organically bound tritium (OBT) is 2.3 times larger than that for ingestion of the same concentration of tritium in the free water of plants and animals. However, because the concentration of free-water tritium exceeds the concentration of tritium in organic matter for most dietary components (per kilogram) in LLNL's ingestion dose assessment, free-water tritium makes the dominant contribution to dose. LLNL's standard operating procedure has been to disregard the OBT contribution.

New LLNL Tritium Model That Distinguishes Doses from HTO, HT, and OBT

A new model, called NEWTRIT, was developed at LLNL in 2000 to better evaluate the dose from tritium releases. The CAP88-PC model, as noted above, treats only the dispersion and dose consequences of the tritiated water vapor form of tritium (HTO). The new model distinguishes between releases to air of HT and HTO and takes into account the effects on dose of conversion of HT to HTO in the environment. NEWTRIT also accounts for dose from organically bound tritium in the diet. The NEWTRIT model was programmed into CAP88-PC and used to generate dose results for comparison with default CAP88-PC model runs. NEWTRIT uses the latest dose coefficients for HT, HTO, and OBT of the International Commission on Radiological Protection (ICRP 1995, 1996). This new model is discussed in the *LLNL NESHAPs 2000 Annual Report* (Gallegos et al. 2001).

The NEWTRIT model has been described in detail by its authors in a paper accepted for publication in *Health Physics* (Peterson and Davis 2001). It will be presented to the EPA and DOE for consideration of its use in regulatory compliance modeling.

Special Modeling Problems

Nonstack releases may require special measurements and calculations to characterize the source. Both the Livermore site and Site 300 provide important examples in this regard.

Diffuse Sources

Nonstack releases often fall into the classification of "diffuse sources." One example is the leakage of tritium-contaminated water from an underground

retention tank at Building 292 at the Livermore site, which results in the release of tritium to the atmosphere via soil moisture evaporation and root-uptake and transpiration by plants—from one pine tree in particular. A discussion of this source appears in the Livermore Site Diffuse Sources section in the *NESHAPs 1993 Annual Report* (Harrach et al. 1994); subsequent NESHAPs annual reports provide updates. Emissions from certain difficult-to-characterize sources sometimes can be inferred from data obtained by LLNL's routine surveillance air monitoring program, in which the ambient air at selected locations within and outside Laboratory boundaries is continuously monitored for tritiated water vapor and radioactive particles. For example, the operations in the Building 612 waste storage yard at the Livermore site are characterized using data from an air monitor in the yard. Another example is the diffuse source caused by resuspension of depleted uranium in soil at Site 300; an air monitor at the location of the SW-MEI measures the annual-average concentration of uranium in air. A theoretical model described in the *NESHAPs 1995Annual Report* (Gallegos et al. 1996) was developed to distinguish between the contribution made to these Site 300 data by LLNL-operations-contributed uranium, compared to the considerably larger contribution from naturally occurring uranium. The routine air surveillance monitoring program also has been particularly useful in registering the magnitude of unplanned releases; an example of this type is provided by the accidental release of curium-244 from Building 513 in 1997, discussed in the Executive Summary, Chapter 2, and Chapter 12 of LLNL's *Environmental Report 1997* (Harrach et al. 1998), as well as in the *NESHAPs 1997 Annual Report* (Gallegos et al. 1998).

Modeling Dose Impacts from Explosives Experiments at Site 300

Special consideration must be given to modeling releases of radionuclides into the atmosphere from explosive tests at Site 300, compared to conventional stack or area sources. During experiments, an explosive device, which may contain depleted uranium, is placed on an open-air firing table and detonated. A cloud of explosive decomposition products forms promptly (on a roughly 1-minute time-scale) over the firing table, typically reaching a height of several hundred meters, and disperses as it is carried downwind. (The depleted uranium does not contribute to the explosive energy, which is entirely of chemical origin.)

In the absence of measurements of the cloud properties, we assume for compliance modeling purposes that it instantaneously reaches an initial height and size governed by known empirical scaling laws for detonations, in which the scaling parameter is the TNT-equivalent explosive mass. The specific equations we use for the maximum elevation, H_{max}, reached by the plume and the diameter, D, of the cloud of decomposition products have been described elsewhere (Harrach et al. 1998, Harrach 1998).

Transport and dispersion of the quickly formed cloud are modeled using a Gaussian-plume air-dispersion code. A puff-code-based modeling methodology was submitted to EPA for approval in 1992 (Biermann et al. 1993). It would treat these transient explosive events as short-duration bursts or puffs, would incorporate some of the effects of the hilly terrain at Site 300, and would use meteorological data appropriate to the cloud-dispersal period. EPA decided that, from the standpoint of regulatory compliance, the use of CAP88-PC to model these explosives experiments was adequate, despite the recognized difficulties. CAP88-PC simulates each explosive experiment or shot as a continuous, year-long, stack-type emission (i.e., the total activity released in a time period of order 1 minute in the explosion is treated as though it were released gradually over the course of an entire year), with meteorological data corresponding to

annual-average conditions at Site 300. As inputs to the code, the scaling results for H_{max} and D are used as a fixed plume height and stack diameter.

LLNL uses isotopic ratios for depleted uranium and determines the contribution of each isotope to dose. The isotopes uranium-238, uranium-235, and uranium-234 occur in the weight-fractions 0.998, 0.002, and 5×10^{-6}, respectively. The inventory for each explosive experiment specifies the mass of depleted uranium used: M_{DU}(kg). The number of curies for each isotope in the cloud is then given by the product of its weight fraction, the mass of depleted uranium, and the specific activity (number of curies per kilogram) of the isotope. Uranium-235 has a specific activity of 2.14×10^{-3} Ci/kg, so that multiplying by the weight fraction 0.002 gives the number of curies of uranium-235 in the cloud to be 4.28×10^{-6} (Ci/kg) $\times$ M_{DU}(kg). The corresponding expressions for uranium-238 and uranium-234 are 3.32×10^{-4} (Ci/kg) $\times$ M_{DU}(kg) and 3.10 x 10^{-5} (Ci/kg) $\times$ M_{DU}(kg), respectively.

In the absence of detailed data about the explosive experiments, several highly conservative assumptions are made in our calculations. These assumptions are (1) 100% of the depleted uranium present in the experiment is completely aerosolized and dispersed as a cloud (i.e., the release-to-air fraction is 1); (2) the median particle size is the CAP88-PC default value of 1 µm; and (3) the lung clearance class for inhaled material is class Y. (Note: Clearance of inhaled material from the lung to the blood or to the gastrointestinal tract depends on the chemical form [e.g., U_3O_8] of the radionuclide and is classified as D, W, and Y, respectively, for clearance times of order days, weeks, and years.) These assumptions may produce a dose that is too high by a factor of 10 or more. We believe a more realistic release-to-air fraction for the uranium is no greater than 0.2, but we lack sufficient documentation to use a value other than 1.0. Also, the median particle size may be much larger than 1 µm, and a sizable fraction of the aerosolized particles might be more properly characterized by lung clearance class D, which produces a dose by inhalation of depleted uranium that is smaller by a factor of about 16 compared to class Y. Even with these assumptions, the MEI and SW-MEI individual doses as well as the collective or population dose that we calculate annually for the explosive experiments are very small compared with natural background levels and regulatory standards (see the "Summary and Conclusions" section of this chapter).

Radiological Doses to the Public from 2000 LLNL Operations

Nearly 170 emission points were evaluated in the 2000 modeling runs. These emission sources were of several types: stacks and other exhaust pathways from buildings, diffuse area sources generally located external to buildings, and open-air firing tables at Site 300 where explosives experiments were conducted.

The principal diffuse sources at the Livermore site in 2000 were the waste storage, management, and drum sampling areas at the Building 612 Yard, a waste accumulation area located outside the Tritium Facility (Building 331), and the Building 514 Evaporator. The principal diffuse source at Site 300 was resuspension of depleted uranium over the total land area of the site.

This section summarizes the main results of LLNL's calculations for 2000 operations and exhibits the trends in these results over recent years. For further details, especially regarding the diffuse sources at the two sites, see the *LLNL NESHAPs 2000 Annual Report* (Gallegos et al. 2001).

Dose Breakdown by Facility

Table 13-1 lists all LLNL facilities and diffuse sources having the potential to release radioactivity into the environment during 2000. For each facility or building, the table gives the number of stacks or other exhaust avenues discharging radionuclides; lists the dose to the SW-MEI caused by the single, most dominant emission point at each facility; and identifies the types of operations occurring in the building or facility or the nature of the diffuse source. Corresponding data are included for the Site 300 explosive experiments. Facilities in which no operations using radionuclides took place in 2000 or in which any radionuclides present were encapsulated or sealed for the entire year are excluded from **Table 13-1**.

A principal feature shown in **Table 13-1** is that LLNL has a large number of very small radioactive sources and only a few that could be considered significant. As shown more clearly in subsequent tables, about a half-dozen sources account for nearly all of the dose to members of the public, and the total dose is quite small compared with federal standards for radiation protection of the public.

Unplanned Releases

There were no unplanned atmospheric releases at the Livermore site or Site 300 in 2000.

Doses to Public Site-Wide Maximally Exposed Individuals

Total dose to the site-wide maximally exposed (public) individual (SW-MEI) at the Livermore site in 2000 was 0.37 μSv (0.037 mrem), divided 43%–57% between point and diffuse (extended area) source emissions. This sort of division between dose levels attributed to these two types of sources contrasts with previous years, when doses to the public from stack emissions at the Livermore site considerably exceeded those from diffuse sources. Furthermore, in 2000, for the first time, a diffuse source—the Building 612 Yard for waste storage and management—was the single largest contributor to the SW-MEI dose, accounting for 0.15 μSv (0.015 mrem), or more than 40% of the total. Emissions from the two 30-m stacks at the LLNL Tritium Facility (Building 331), historically the leading source, accounted for an unusually small 23% of the total dose.

The 2000 Livermore site SW-MEI dose is down by a factor of 2.7 from the previous year's value, principally owing to a nearly sixfold decrease in HTO emissions from the stacks of the Tritium Facility (Building 331): 1.3×10^{12} Bq (35.4 Ci) of HTO in 2000, compared to 7.9×10^{12} Bq (214 Ci) the previous year. Emissions of HT from these stacks were also low in 2000, amounting to less than 1.8×10^{11} Bq (4.8 Ci), which is about 7% of the previous year's value.

The foregoing dose numbers were obtained by neglecting contributions to dose from HT releases, relative to HTO releases; see the section on Assessment Assumptions Regarding Tritium. Calculating dose as recently directed by EPA (treating HT as though it were HTO in CAP88-PC model runs) only slightly increases the total annual dose to the SW-MEI from Livermore-site operations in 2000, to 0.38 μSv (0.038 mrem), since little HT was released.

The calculated EDE to the SW-MEI at Site 300 in 2000 was 0.19 μSv (0.019 mrem). Seventy-nine percent, or 0.15 μSv (0.015 mrem), was attributed to releases to air of depleted uranium in explosives experiments conducted at the Building 851 firing table. The remaining 21% of the total was attributed to Site 300 diffuse sources. Resuspension of operations-contributed uranium in Site 300 surface soils (i.e., uranium deposited into the soils by LLNL experiments and other activities as opposed

Table 13-1. Sources of radiation dose from LLNL releases (measured and potential) to air: stacks and other exhaust pathways from buildings containing radiological operations, and diffuse area sources[a,b]

Bldg	Facility	Potential emission points	Maximum EDE[c] (μSv/y)	Operations
Livermore site point sources				
131 Highbay	Offices and laboratories, Mechanical & Electrical Engineering	3	8.6×10^{-10}	Storage and display of post-test materials
132N	Offices and laboratories; Chemistry & Materials Sciences; Nonproliferation, Arms Control & International Security (NAI); and others	6	1.0×10^{-3}	Preparation of samples for radiochemical analysis; analysis of aqueous solutions and waste samples
132S	See Building 132N	1	2.1×10^{-10}	Transfer of uranium
151	Isotope Sciences Chemistry & Materials Science Environmental Services Laboratory	33	3.4×10^{-3}	Application of nuclear and isotope sciences to a wide range of research; sample analysis of waste streams and environmental media for radionuclide content
175	Space Action Team	6	0.0[d]	Operations discontinued
177	Space Action Team	1	0.0[d]	Operations discontinued
194	Physics & Space Technology	4	5.2×10^{-5}	High-energy linear accelerator, positron beam generation and experiments; materials science experiments
212	Physics & Space Technology	2	8.5×10^{-11}	Physics experiments, residual contamination from previous operation of rotating target neutron source (no longer operating)
231	Chemistry & Materials Science; Engineering, Weapons Engineering; Safeguards & Security	17	1.4×10^{-6}	Materials research and testing, metals processing and characterization, electron-beam welding, grinding/ polishing, casting, microscopy, sample preparation, storage
235	Chemistry & Materials Science	5	3.7×10^{-7}	Material structure studies, precision cutting, ion implantation, metallurgical studies, sample preparation
241	Chemistry & Materials Science	6	1.8×10^{-4}	Materials properties research and testing on uranium; hybridization studies with nucleic acids from soil bacteria
251	Heavy Elements Facility, Physics & Space Technology			Storage of transuranic isotopes prior to disposal
	Seismically hardened area	4	0.0[d]	
	Unhardened areas	28	1.4×10^{-5}	
253	Hazards Control	10	2.8×10^{-8}	Radiochemical analysis and counting of samples
254	Hazards Control	4	5.0×10^{-10}	Bioassays; analytical services; urine analyses for radionuclides
255	Hazards Control	2	9.9×10^{-5}	Radiation standards and instrument calibration
281	Energy & Environmental	5	4.0×10^{-7}	Sample preparation, radioactivity migration studies, tracers, flow studies
282	Energy & Environmental	1	6.2×10^{-12}	Residual tritium contamination from past activities

Table 13-1. Sources of radiation dose from LLNL releases (measured and potential) to air: stacks and other exhaust pathways from buildings containing radiological operations, and diffuse area sources[a,b] (continued)

Bldg	Facility	Potential emission points	Maximum EDE[c] (μSv/y)	Operations
292	Environmental Programs	3	3.9×10^{-5}	Tritium contamination from prior operations
298	NIF Programs Research	3	5.7×10^{-6}	Laser fusion targets research and development
321	Mechanical Engineering, Materials Fabrication	6	3.4×10^{-7}	Milling, shaping, heat treating, and machining depleted uranium parts
322	Mechanical Engineering	1	5.0×10^{-9}	Cleaning and plating of depleted uranium
327	Mechanical Engineering	1	1.9×10^{-7}	Nondestructive ultrasonic material evaluation
331	Tritium Facility, Defense & Nuclear Technologies	2	7.4×10^{-2}[d,e]	Tritium research and development, facility decontamination and decommissioning operations
332	Plutonium Facility, Defense Sciences Program	8	0.0[d]	Plutonium research
341	Laser Directorate	1	1.1×10^{-9}	Equipment decontamination
361	Biology and Biotechnology Research	9	1.0×10^{-7}	DNA labeling, hybridization, and enzyme assay; human genome research; P-32 labeling; DNA protein interaction studies
362	Biology and Biotechnology Research	2	4.6×10^{-7}	Characterization of metabolic pathways
363	Biology and Biotechnology Research	2	1.6×10^{-13}	Human urine sample project, high pressure liquid chromatography (HPLC) analysis
364	Biology and Biotechnology Research	3	8.6×10^{-8}	DNA and protein extraction, accelerator mass spectrometry (AMS) sample preparation
365	Biology and Biotechnology Research	2	2.0×10^{-13}	Housing research animals, animal research, equipment decontamination
366	Biology and Biotechnology Research	1	3.2×10^{-7}	DNA labeling
378	Energy & Environment Directorate	2	2.6×10^{-8}	Radioactive tracer handling
491	Site Action Team	1	0.0[d]	Operations discontinued
513	Hazardous Waste Management	2	4.3×10^{-5}	Sampling, treatment, and storage of hazardous, mixed, and radioactive waste; process optimization and treatability studies
514	Hazardous Waste Management	3	6.0×10^{-2}	Waste consolidation, waste treatment
612	Hazardous Waste Management	3	5.9×10^{-3}	Waste sampling; analysis of waste treatment and treatability samples
Site 300 point sources				
801	Flash x-ray (FXR) machine	1	1.8×10^{-7}	Flash x-ray photography of explosives experiments
810A	Site 300 firing table support	3	2.8×10^{-6}	Assembly of explosives test devices
810B	Site 300 firing table support	3	7.8×10^{-7}	Assembly of explosives test devices
851	Site 300 firing table at Building 851	—[f]	1.5×10^{-1}	Detonation of explosives
851	Linear accelerator	1	1.6×10^{-5}	Research

Table 13-1. Sources of radiation dose from LLNL releases (measured and potential) to air: stacks and other exhaust pathways from buildings containing radiological operations, and diffuse area sources[a,b] (continued)

Bldg	Facility	Potential emission points	Maximum EDE[c] (μSv/y)	Operations
Livermore site diffuse sources[g]				
223	Contaminated facility	1	1.2×10^{-6}	Decontamination and decommissioning activities
292	Spill area	1	7.2×10^{-7}	Evaporation and transpiration of tritiated water from underground tank leakage
331	Tritium Facility (external)	1	4.4×10^{-2}	Outdoor temporary placement of contaminated parts and equipment awaiting transport and storage
514	Hazardous Waste Management Tank Farm	1	9.2×0^{-3}	Processing of liquid hazardous, mixed, and radioactive wastes in open-topped tanks
612	Hazardous Waste Management storage yard	1	1.5×10^{-1}	Storage of low-level tritium waste
612	Hazardous Waste Management waste areas	1	8.5×0^{-8}	Drum sampling in Building 612 yard and all LLNL waste accumulation areas (WAAs)
614	Hazardous Waste Management yard	1	1.3×10^{-7}	Repackaging of waste scintillation cocktail
—	Southeast quadrant of Livermore site	1	4.5×10^{-3}	Ground contaminated with plutonium-239 from past waste management operations
Site 300 diffuse sources[g]				
—	All Site 300 land area	1	3.7×10^{-2}	Resuspension of uranium in contaminated soil
804	Open area	1	2.1×10^{-6}	Low-level waste staging area

a *LLNL NESHAPs 2000 Annual Report* (Gallegos et al. 2001)

b Areas in which no operations using radionuclides took place in 2000 or in which all radionuclides were encapsulated or sealed for the entire year are not included in this table. Table entries refer to routine operations, not unplanned releases.

c The maximum EDE to the SW-MEI member of the public from the single most dominant emission point for the indicated facility or building. The SW-MEI is defined in the Identification of Key Receptors section.

d The effluents from the facility are monitored. Zeroes refer to monitored values below the minimum detectable concentration, as discussed, for example, in the Air-Emission Data section of the *LLNL NESHAPs 2000 Annual Report* (Gallegos et al. 2001).

e This dose takes into account only HTO emissions from the Tritium Facility stacks. If, instead, the emissions of HTO and HT are combined, and the sum treated as though it were entirely HTO for purposes of evaluating the maximum potential dose to the public, the dose from the principal stack was 0.085 μSv/y, rather than 0.074 μSv/y. (See the "Assessment Assumptions Regarding Tritium" section of this chapter.)

f Open-air dispersal in 2000

g Diffuse sources are described briefly in the "Special Modeling Problems" section of this chapter and more fully in the *LLNL NESHAPs 2000 Annual Report* (Gallegos et al. 2001).

to natural background amounts), was responsible for 0.037 μSv (0.0037 mrem), which was nearly all of the dose from diffuse sources. **Table 13-2** summarizes doses to the SW-MEIs for the Livermore site and Site 300 over the past eleven years.

Table 13-3 shows the Site 300 SW-MEI dose values attributed to firing table experiments for 1990 through 2000, exhibited along with the total amounts of depleted uranium and the total quantity of high explosives used each year in the experiments. (Only explosives experiments that included depleted uranium are considered here; most have none.) The 2000 total is indicative of reduced firing table activity compared to typical levels in the past decade (see also the "point source dose" column for Site 300 in **Table 13-2**). The **Table 13-3** data indicate that the SW-MEI dose is increased by using more depleted uranium and smaller quantities of explosives (producing lower debris-cloud heights) in the experiments.

The facilities that were primarily responsible for the LLNL doses to the public are listed in **Table 13-4**. These facilities collectively accounted for approximately 91% of the total dose resulting from Livermore site operations and for more than 99% of the total from Site 300 operations. The principal radionuclide(s) are indicated for each facility. Tritium was the overall dominant radionuclide at the Livermore site, as usual, accounting for almost 75% of the Livermore site dose. Also as usual, practically the entire dose from Site 300 operations was attributed to the isotopes present in depleted uranium having atomic numbers 238, 235, and 234.

Regarding dose pathways of the dominant radionuclides, the relative significance of inhalation and ingestion depends on the assumptions made about the origin of food consumed. For the conditions assumed when assessing individual LLNL doses—namely that milk is imported while the remainder of the food is produced locally—ingestion dose is larger than inhalation dose in the case of tritium, approximately in the ratio 80% to 20%. For uranium, these numbers are nearly reversed: 17% by the ingestion pathway versus 83% via inhalation. For both uranium and tritium, external doses from air immersion and ground irradiation are negligible.

Comparison of Modeling Results to Monitoring Data

Comparisons were made between measured and modeled values of annual-average tritium concentrations (specifically HTO) in air at the Livermore site in 2000 (Gallegos et al. 2001). CAP88-PC model runs used source terms representing the three principal tritium sources at the site: the Building 331 (Tritium Facility) stacks, the Building 612 Yard waste storage area, and an area outside Building 331. Data on concentrations of HTO were collected biweekly throughout the year from LLNL's set of tritium surveillance air monitors; see the maps showing monitor locations in **Figures 5-1** and **5-2** in this report. For the calculation-data comparison, 1 offsite monitor (designated ZON7, notable because it is in the prevailing downwind direction from the sources and is the site of a drinking water supply for the area), and 11 onsite monitors (designated VIS, SALV, POOL, CAFE, MESQ, MET, COW, B331, B514, B624, and B292) were included.

The source terms representing HTO emissions from the Tritium Facility stacks and the area outside Building 331 were determined directly, independent of surveillance air monitoring data, by using continuous stack-effluent-monitoring data and inventory estimates, respectively. However, the Building 612 Yard emission rate was indirectly inferred from a self-consistent back calculation, in which the HTO release rate from the Building 612

Table 13-2. Doses calculated for the SW-MEI for the Livermore site and Site 300, 1990 to 2000

Year	Total dose (μSv)	Point source dose (μSv)	Diffuse source dose (μSv)
Livermore site			
2000	0.37[a]	0.16[a]	0.21
1999	1.0[a]	0.73[a]	0.28
1998	0.49	0.25	0.24
1997	0.97	0.78	0.19
1996	0.93	0.48	0.45
1995	0.41	0.19	0.22
1994	0.65	0.42	0.23
1993	0.66	0.40	0.26
1992	0.79	0.69	0.10
1991	2.3	—[b]	—[b]
1990	2.4	—[b]	—[b]
Site 300			
2000	0.19	0.15	0.037
1999	0.35	0.34	0.012
1998	0.24	0.19	0.053
1997	0.20	0.11	0.088
1996	0.33	0.33	0.0045
1995	0.23	0.20	0.03
1994	0.81	0.49	0.32
1993	0.37	0.11	0.26
1992	0.21	0.21	—[c]
1991	0.44	0.44	—[c]
1990	0.57	0.57	—[c]

a Calculating dose by the alternative method as directed by EPA, the total dose for 2000 was 0.38 μSv and the point source dose was 0.17 μSv; similarly, the total dose for 1999 was 1.2 μSv and the point source dose was 0.94 μSv (see the discussion in the "Assessment Assumptions Regarding Tritium" section of this chapter).

b Point source and diffuse source doses were not reported separately from the total dose for the Livermore site for 1990 and 1991.

c No diffuse emissions were reported at Site 300 for years prior to 1993.

Table 13-3. Annual dose to the SW-MEI from explosives experiments on firing tables at Site 300, 1990–2000, related to the total quantity of depleted uranium used in the experiments and the total quantity of high explosives driving the detonations

Year	Dose to SW-MEI		Total depleted uranium used in experiments (kg)	Total HE[a] used in depleted uranium experiments (kg)
	(μSv)	(mrem)		
2000	0.15	0.015	43	34
1999	0.34	0.034	216	168
1998	0.19	0.019	230	192
1997	0.11	0.011	163	122
1996	0.33	0.033	272	112
1995	0.20	0.020	165	199
1994	0.49	0.049	230	134
1993	0.11	0.011	99	74
1992	0.21	0.021	151	360
1991	0.44	0.044	221	330
1990	0.57	0.057	340	170

a HE = high explosives

Yard diffuse source was adjusted to force agreement with the data provided by the tritium surveillance air monitor in closest proximity (the B624 monitor). The modeling results then agree, by design, with the B624 monitor data, and the meaningful comparison between modeling and measurements involves only the eleven other monitor locations. The results are displayed in **Table 13-5**. The main conclusion was that CAP88-PC air dispersion modeling, taking into account the three leading sources of HTO emissions at the Livermore site and using site-specific meteorological data for 2000, gave results in fairly good agreement with annual-average surveillance air monitoring data. CAP88-PC assumes "flat" terrain, which is appropriate for the Livermore site, but the code's neglect of terrain features such as trees and buildings is expected to produce discrepancies with measurements, even with long-time (one-year) averaging of winds. Generally speaking, the modeling predicted higher concentrations of HTO than were measured (see the "ratio" column in **Table 13-5**). This is a desirable result, particularly for offsite locations such as ZON7 where public exposures could occur, erring on the side of more conservative modeling for regulatory compliance.

The modeled concentration levels were in the right "ball park," agreeing with the data within a factor of five at all but three locations, despite the fact that the emissions and consequently the concentrations were quite low. In the case of two monitors (B331 and CAFE), the difference was approximately a factor of six, and at one monitor (SALV) the difference was almost a factor of eleven. These results are consistent with those found in similar comparisons made the previous three years; see the NESHAPs Annual Reports for 1997 through 1999 (Gallegos et al. 1998; Biermann et al. 1999; Gallegos et al. 2000).

Table 13-4. Major contributors to LLNL's radiation dose to the site-wide maximally exposed (public) individual (SW-MEI) via releases to air, 2000

Facility or operation[a]	Dominant radionuclide(s)	EDE at SW-MEI[b]	
		μSv/y	mrem/y
Livermore site			
B612 Yard Area[c]	Tritium	0.15	0.015
B331/Tritium Facility	Tritium	0.084[d,e]	0.0084[d,e]
B514 Evaporator	Various	0.060	0.0060
B331 External Waste Accumulation Area[c]	Tritium	0.044	0.0044
Sum of all other sources	Various	0.027	0.0027
Total		**0.37**[e,f]	**0.037**[e,f]
Site 300			
B851/firing table	Uranium-238 Uranium-234 Uranium-235	0.15	0.015
Soil resuspension[c]	Uranium-238 Uranium-234 Uranium-235	0.037	0.0037
Total		**0.19**[f]	**0.019**[f]

a The facilities cited here are discussed in the text of this report and in more detail in the LLNL NESHAPs annual reports.

b The SW-MEI is defined in the Identification of Key Receptors section.

c Diffuse sources (see text)

d The dose quoted for the Building 331 Tritium Facility is the collective result of emissions from both stacks.

e Calculating dose as directed by EPA yields 0.095 μSv/y for the Tritium Facility, which raises the total dose to 0.38 μSv/y. (See the "Assessment Assumptions Regarding Tritium" section of this chapter.)

f These Livermore site and Site 300 totals represent 0.37% and 0.19%, respectively, of the federal standard.

Temporal Trends in Dose to the SW-MEI

The trends in dose to the SW-MEI from emissions at the Livermore site and Site 300 over the last 11 years are shown graphically in **Figure 13-1** (see also **Table 13-2**). The general pattern, particularly over the last nine years, shows year-to-year fluctuations around a quite low dose level, staying at or below about 1% of the federal standard.

The SW-MEI dose estimates are intentionally conservative, predicting potential doses that are several times higher than would actually be experienced by any member of the public. Potential doses from Site 300 firing table operations are especially so, as explained in the "Special Modeling Problems" section of this chapter.

Collective Doses to Potentially Exposed Populations

Population doses, or collective EDEs, for both the Livermore site and Site 300 were evaluated using CAP88-PC, taking into consideration persons living within an EPA-specified 80-kilometer (50-mi) radius of the site centers. The highest

Table 13-5. Comparison of measured and modeled annual-average concentrations of tritiated water vapor (HTO) in air at selected Livermore site locations, 2000

Air monitor (name)	Measured concentration (pCi/m^3)	Modeled[a] concentration (pCi/m^3)	Ratio of modeled-to-measured concentrations	Modeled concentration of tritium in air contributed by the indicated source (pCi/m^3)		
				B331 Stacks	B612 Yard	B331 Outside
B624	88.6	89.9	1.01	0.48	89	0.41
B331	12.1	68.9	5.69	0.054	1.8	67
B514	50.0	49.7	0.99	0.23	49	0.42
VIS	1.28	3.79	2.96	1.4	1.7	0.69
POOL	2.07	9.02	4.35	0.72	1.8	6.5
CAFE	1.09	6.68	6.13	0.68	2.4	3.6
COW	0.908	0.95	1.05	0.22	0.25	0.48
B292	1.49	1.70	1.14	0.25	0.45	1.0
SALV	0.738	7.99	10.8	0.18	7.6	0.21
MESQ	0.565	2.80	4.96	0.17	0.53	2.1
MET	0.484	1.14	2.36	0.18	0.26	0.70
ZON7	0.381	1.14	2.99	0.73	0.18	0.23
(CRED)	—[b]	4.99	—[b]	1.5	2.7	0.79

a This result takes into account the three most significant tritium sources; it is the sum of the three contributions shown in the far-right column.

b The CRED location does not have a tritium surveillance air monitor, but is included since it marks the location of the SW-MEI.

population concentrations in this range are found in the cities of Livermore, Tracy, Modesto and Stockton, and the large urban centers of Oakland, San Francisco, and San Jose. Updated population distributions centered on the two sites were prepared in 2001, as described in Section VI of the *LLNL NESHAPs 2000 Annual Report* (Gallegos et al. 2001). The circles of 80-km radius envelope 6.9 million residents for the Livermore site and 6.0 million for Site 300.

The population dose or collective EDE attributed to 2000 Livermore site operations was 0.0047 person-Sv (0.47 person-rem). This is about 3.6-times lower than the 1999 result of 0.017 person-Sv (1.7 person-rem). The decrease compared to 1999 was principally due to the previously noted factor-of-six reduction in emissions of HTO from the Tritium Facility stacks in 2000. When calculated as directed by EPA (i.e., treating HT as though it were HTO), the 2000 population dose from Livermore site operations is increased about 11%, to 0.0052 person-Sv (0.52 person-rem).

The population dose from Site 300 operations in 2000 was 0.025 person-Sv (2.5 person-rem). This is lower by a factor of 4.4 than the value registered in each of the previous two years, corresponding

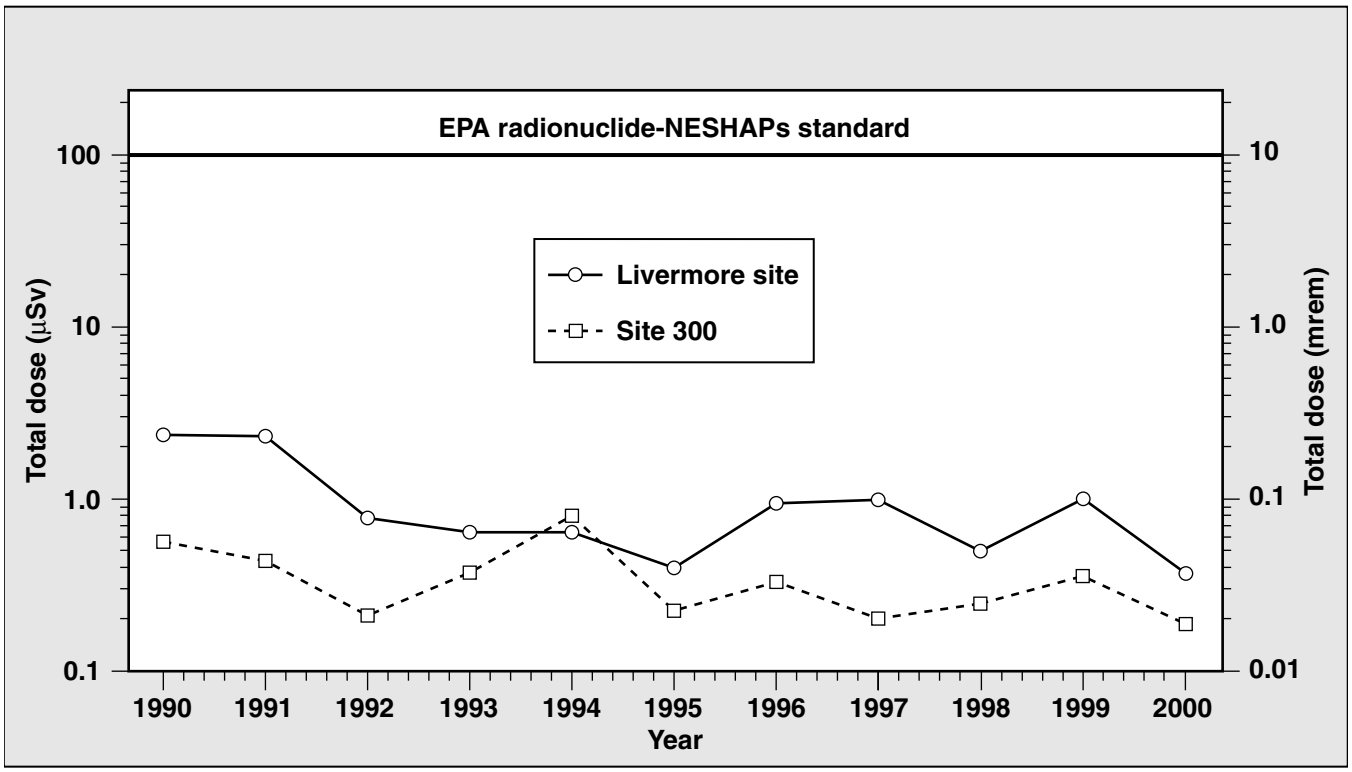


Figure 13-1. Annual dose to the site-wide maximally exposed individual member of the public, 1990 to 2000

primarily to the reduction in quantity of depleted uranium used in explosives experiments (see **Table 13-3**).

Doses to the Public Placed in Perspective

These levels of variation in population and SW-MEI doses from one year to the next are within the expected range of operations-driven fluctuations in small radiation quantities. A frame of reference to gauge the magnitude of these LLNL doses is provided in **Table 13-6**. The table compares the conservatively estimated population doses and doses to the maximally exposed public individuals caused by LLNL operations against average doses received in the United States from exposure to natural background radiation and medical treatments. The population doses attributed to LLNL operations in 2000 are more than 750,000-times smaller than ones from natural background radiation; the estimated maximum potential doses to individual members of the public from operations at the two LLNL sites in 2000 are 8000-times smaller than ones from background radiation in the natural environment.

Estimate of Dose to Biota

DOE has worked the past six years to develop standards for protection of the natural environment from the effects of ionizing radiation, culminating in its detailed (draft) guidance document "DOE Standard (Proposed): A Graded Approach for Evaluating Radiation Doses to Aquatic and Terrestrial Biota" (U.S. DOE 2000). The operating principle used for radiological protection in

Table 13-6. Comparison of background (natural and man-made) and LLNL radiation doses, 2000

Location/source	Individual dose[a]		Population dose[b]	
	(μSv)	(mrem)	(person-Sv)	(person-rem)
Livermore site sources				
Atmospheric emissions	0.37[c]	0.037[c]	0.0047[c]	0.47[c]
Site 300 sources				
Atmospheric emissions	0.19	0.019	0.025	2.5
Other sources[d]				
Natural radioactivity[e,f]				
Cosmic radiation	300	30	1,900	190,000
Terrestrial radiation	300	30	1,900	190,000
Internal (food consumption)	400	40	2,500	250,000
Radon	2,000	200	12,500	1,250,000
Medical radiation (diagnostic procedures)[f]	530	53	3,300	330,000
Weapons test fallout[f]	11	1.1	68	6,800
Nuclear fuel cycle	4	0.4	25	2,500

a For LLNL sources, this dose represents that experienced by the SW-MEI member of the public.

b The population dose is the collective (combined) dose for all individuals residing within an 80-km radius of LLNL (approximately 6.9 million people for the Livermore site and 6.0 million for Site 300), calculated with respect to distance and direction from each site.

c Calculating dose by the alternative method as directed by EPA, the individual dose was increased to 0.38 μSv (0.038 mrem), and the population dose to 0.0052 person-Sv (0.52 person-rem); see the "Doses to Public Site-Wide Maximally Exposed Individuals" and "Collective Doses to Potentially Exposed Populations" sections.

d From National Council on Radiation Protection and Measurements (NCRP 1987a, b)

e These values vary with location.

f This dose is an average over the U.S. population.

the past—that by protecting man, other living things are also likely to be sufficiently protected—is no longer considered adequate.

The guidance includes a biota manual, spreadsheets, and a database giving biota concentration guides (BCGs). Cases where human access to an area of exposure is restricted or exposure pathways favor biota exposure are especially important to consider. The effort required to show compliance is minimized by several features of the guidance: its use of a graded approach; its allowance of use of *existing* generic and site-specific data (not requiring new monitoring programs tailored to biota); and the fact that current and proposed standards are not very restrictive. Regarding the latter, the limit on absorbed dose is 10 mGy/d (1 rad/d) for aquatic animals and terrestrial plants, and 1 mGy/d (0.1 rad/d) for terrestrial animals. See Appendix D, Part D-1, Radiation Basics, and the Glossary for a discussion of radiation units.

Screening calculations for LLNL impacts were performed in 2000 using the spreadsheet provided with the guidance. Each radionuclide in each medium (soil, sediment, surface water) is assigned a

derived concentration limit in the guidance. For each measured maximum concentration input to the spreadsheet, a fraction of the derived concentration limit for that radionuclide is automatically calculated, and the fractions summed for each medium. For aquatic biota, the sum of the fractions for water exposure are added to the sum of the fractions for sediment exposure. Similarly, the fractions for water and soil are summed for terrestrial biota. If the sums for the aquatic and terrestrial biota are both less than 1.0, the site has passed the screening analysis, and the biota are assumed to be protected without further analysis.

In the LLNL assessment, the maximum concentration of each radionuclide measured in soils, sediments, and surface waters during 2000, whether measured on the Livermore site, offsite in the Livermore Valley, or at Site 300, was entered into the screening calculation. Principal measured radionuclides were cesium-137, tritium, plutonium-239, thorium-232, uranium-234, uranium-235 and uranium-238. For LLNL, the sum of the fractions for aquatic biota was 0.0724, and the sum for terrestrial biota was 0.0165. Both are indicative of doses to aquatic and terrestrial biota from LLNL operations that are well below allowable dose limits.

Summary and Conclusion

The annual radiological dose from all emissions at the Livermore site and Site 300 in 2000 was found to be well below the applicable standards for radiation protection of the public, in particular the NESHAPs standard. This standard limits to 100 μSv/y (10 mrem/y) the EDE to any member of the public, arising as a result of releases of radionuclides to air from DOE facilities. Using EPA-mandated computer models, actual LLNL meteorology, and population distributions appropriate to the two sites, the potential doses to the LLNL SW-MEI members of the public from operations in 2000 were evaluated, with the following results:

- Livermore site: 0.37 μSv (0.037 mrem)—43% from point-source emissions, 57% from diffuse-source emissions—calculated by neglecting the dose contribution of HT releases relative to HTO releases. If HT is treated as though it were HTO, as directed by EPA, the total annual dose to the SW-MEI from Livermore site operations is increased slightly to 0.38 μSv (0.038 mrem).

- Site 300: 0.19 μSv (0.019 mrem)—79% from explosive experiments, which are classified as point-sources, 21% from diffuse-source emissions.

The major radionuclides accounting for the doses were tritium at the Livermore site and the three isotopes in depleted uranium (uranium-234, uranium-235, and uranium-238) at Site 300. The only significant exposure pathway was release of radioactive material to air, leading to doses by inhalation and ingestion.

The collective EDE or population dose attributable to LLNL operations in 2000 was estimated to be 0.0047 person-Sv (0.47 person-rem) for the Livermore site and 0.025 person-Sv (2.5 person-rem) for Site 300. Calculating dose as directed by EPA, the Livermore site value was 0.0052 person-Sv (0.52 person-rem). These doses include potentially exposed populations of 6.9 million people for the Livermore site and 6.0 million people for Site 300 living within a distance of 80 km from the site centers, based on an updated population analysis.

The doses to the MEI members of the public resulting from Livermore site and Site 300 operations in 2000 were below 0.4% of the federal standard and were about 8,000 times smaller than the dose from background radiation. The population doses from LLNL operations in 2000 were more than 750,000 times smaller than those caused by natural radioactivity in the environment (see **Table 13-6**).

Potential doses to aquatic and terrestrial biota from LLNL operations were assessed and found to be well below DOE allowable dose limits.

We conclude that the potential radiological doses from LLNL operations were well below regulatory standards and were very small compared with doses normally received by these populations from natural background radiation sources, even though highly conservative assumptions were used in the determinations of LLNL doses. These maximum credible doses to the public indicate that LLNL's use of radionuclides had no significant impact on public health during 2000.